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Original Article

Mechanical and Durability Performance of Fiber-Reinforced Geopolymer Concrete

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Abstract *- This study investigates the effects of Fiber reinforcement on the workability, mechanical properties, and durability of Geopolymer Concrete (GPC) and Conventional Concrete (CC) mixes. Fly ash and ground granulated blast furnace slag (GGBS) were used as binders, with river sand and manufactured sand (M-sand) as fine aggregates. Polypropylene and steel Fibers were incorporated to evaluate their impact on workability, compressive strength, flexural strength, and modulus of elasticity. Durability tests were conducted to assess long-term performance, including sulphate resistance, acid resistance, and water absorption. The novelty of this study lies in the combined use of M-sand and Fiber reinforcement within GPC, a relatively unexplored combination, highlighting its potential for improving both mechanical and durability properties. The results showed that adding Fibers decreased workability but significantly enhanced mechanical properties and durability. Steel Fiber-reinforced GPC, in particular, exhibited the highest compressive and flexural strengths and superior durability in aggressive environments. The study demonstrates that Fiber-reinforced GPC, with sustainable materials like fly ash, GGBS, and M-sand, can be a viable alternative to conventional concrete, offering enhanced structural performance and environmental benefits. The findings provide insights into the optimization of Fiber-reinforced GPC mixes for modern construction applications.*

Keywords *- Geopolymer Concrete, Fiber reinforcement, M-sand, Mechanical properties, Durability.*

1. Introduction

Geopolymer Concrete (GPC) has emerged as a promising sustainable alternative to Conventional Concrete (CC). Developed to reduce the carbon footprint associated with traditional cement production, GPC uses industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as the primary binders instead of cement. These materials, when combined with an alkaline activator, undergo geopolymerization, forming a stable, durable, and environmentally friendly matrix. The concept of geopolymerization was first introduced by Davidovits (1989). Since then, the use of GPC has gained traction due to its excellent mechanical properties and superior resistance to chemical attacks.

1.1. Literature Review

Geopolymer concrete (GPC) is gaining traction as a sustainable alternative to conventional concrete, particularly due to its use of industrial by-products like fly ash and Ground Granulated Blast-furnace Slag (GGBS). Fly ash, a by-product of coal combustion improves workability, reduces heat of hydration, and enhances long-term strength in GPC, making it a valuable precursor material [1]. GGBS, derived from iron production, further enhances the mechanical properties and durability of GPC by refining its microstructure, enhancing resistance to aggressive chemicals, and boosting structural integrity [2]. M-sand, or manufactured sand, is increasingly used as a substitute for natural river sand, addressing the scarcity of natural resources. M-sand is produced by crushing hard granite stones, resulting in angular particles that enhance bonding in concrete, improve mechanical strength, and reduce porosity, contributing to the durability of both conventional and geopolymer concrete mixes [3, 4]. The use of M-sand in GPC aligns with sustainable construction practices by reducing reliance on natural sand and enhancing the overall performance of the concrete mix [5]. Fiber reinforcement has become an established method for improving concrete tensile strength, ductility, and crack resistance. In Fiber-Reinforced Concrete (FRC), materials such as steel, polypropylene, glass, and carbon fibers mitigate the brittleness of cementitious materials, control cracking due to shrinkage and external loads, and improve post-cracking behavior [6, 7]. In GPC, fibers provide additional reinforcement within the geopolymer matrix, enhancing flexural strength, toughness, and crack resistance. Recent studies indicate that steel fibers, in particular, improve load distribution and crack control, while polypropylene fibers reduce plastic shrinkage and enhance durability [8]. Recent investigations also highlight the effectiveness of hybrid fiber systems. Some research reported that combining steel and polypropylene fibers in GPC offers synergistic benefits, enhancing compressive strength, impact resistance, and flexural performance compared to traditional FRC [9, 10]. Many of them explored the benefits of glass and carbon fibers in GPC, noting improved crack resistance and increased impact strength [11-14]. The performance of both conventional and geopolymer concrete depends on workability, mechanical properties, and durability. Fiber addition can reduce workability, though this can be managed through optimized mix design. M-sand and fiber-reinforced GPC present unique challenges for achieving suitable slump values, but well-designed mixes address these issues effectively [15]. Durability assessments show that fiber-reinforced GPC has superior long-term resistance in aggressive environments compared to conventional concrete, with fly ash and GGBS contributing to a denser microstructure and lower porosity, which enhances durability [10, 15].

Although GPC has been widely studied, the combined effects of fiber reinforcement and the use of sustainable aggregates like M-sand in geopolymer concrete require further investigation. While fiber-reinforced conventional concrete has been well-explored, the unique interaction between fibers and the geopolymer matrix presents an opportunity to enhance both mechanical properties and durability in GPC. The primary research gap lies in understanding how different fiber types (e.g., steel and polypropylene) and sustainable aggregate (such as M-sand) affect the balance between workability and mechanical performance in fiber-reinforced GPC mixes. Additionally, limited studies have investigated the durability of fiber-reinforced GPC, particularly in aggressive environmental conditions like sulphate and acid exposure. This study aims to fill this gap by comprehensively analysing fiber-reinforced GPC and evaluating its performance across workability, mechanical, and durability parameters. The combination of GGBS, fly ash, steel fibers, polypropylene fibers, and M-sand offers a novel approach to enhancing the performance of geopolymer concrete for modern construction applications.

This study focuses on using steel and polypropylene fibers in concrete mixes containing M-sand and river sand as fine aggregates. Mechanical performance, including compressive strength, flexural strength, and modulus of elasticity, will be evaluated alongside durability tests for sulphate resistance, acid resistance, and water absorption.

2. Materials and Methodology

This section outlines the materials used and the methodology adopted for preparing both conventional and geopolymer concrete mixes. The following materials were used: cement, fly ash, ground granulated blast furnace slag (GGBS), fine aggregate (river sand and M-sand), polypropylene fibers, steel fibers, and alkaline activators (sodium hydroxide and sodium silicate solutions). The proportions and properties of each material were based on relevant standards.

2.1. Cement, Fly ash and GGBS

Ordinary Portland Cement (OPC) of 53 grade was used for conventional concrete, conforming to IS 12269:2013 [15]. In the Geopolymer Concrete (GPC) mixes, fly ash (70%) and GGBS (30%) were used as binders in place of cement. The fly ash was of Class F, complying with IS 3812:2003 [16], and the GGBS adhered to IS 12089:1987 [17] standards. The chemical properties of cement, fly ash, and GGBS are listed in Table 1, and the physical properties are listed in Table 2.

Table 1. Chemical composition of binders

Component	Composition (%)		
	Cement	Fly Ash	GGBS
CaO	66.67	1.02	34.48
SiO_2	18.91	52.96	30.61
Fe_2O_3	4.94	11.02	0.584
Al_2O_3	4.51	26.23	15.24
SO_3	2.5	1.28	1.85
MgO	0.87	0.38	6.79
K_2O	0.43	2.82	-
Na_2O	0.12	0.51	-
TiO_2	-	2.54	1.05
Loss of ignition	1.05	0.52	2.1

Table 2. Physical properties of binders

Description	Cement	Fly Ash	GGBS
Size (μ)	90	10-50	0.4-40
Specific gravity	3.15	2.3	2.02
Specific Surface area (m^2/kg)	290	343	422

2.2. Aggregates

River sand and manufactured sand (M-sand) were used as fine aggregates, and crushed granite with a maximum size of 20 mm was used for coarse aggregates, adhering to the IS 383:2016 guidelines. Aggregates are sourced locally; river sand and M-sand are in zone II, and coarse aggregate is graded. The physical properties are presented in Table 3, and the partial distribution curves are shown in Figure 1.

Table 3. Physical properties of aggregates

Description	River Sand	M-Sand	Coarse aggregate
Specific gravity	2.65	2.65	2.7
Water absorption (%)	1.2	3.07	0.5
Silt content (%)	2.2	4.8	1
Fineness modulus	2.85	2.9	7.1

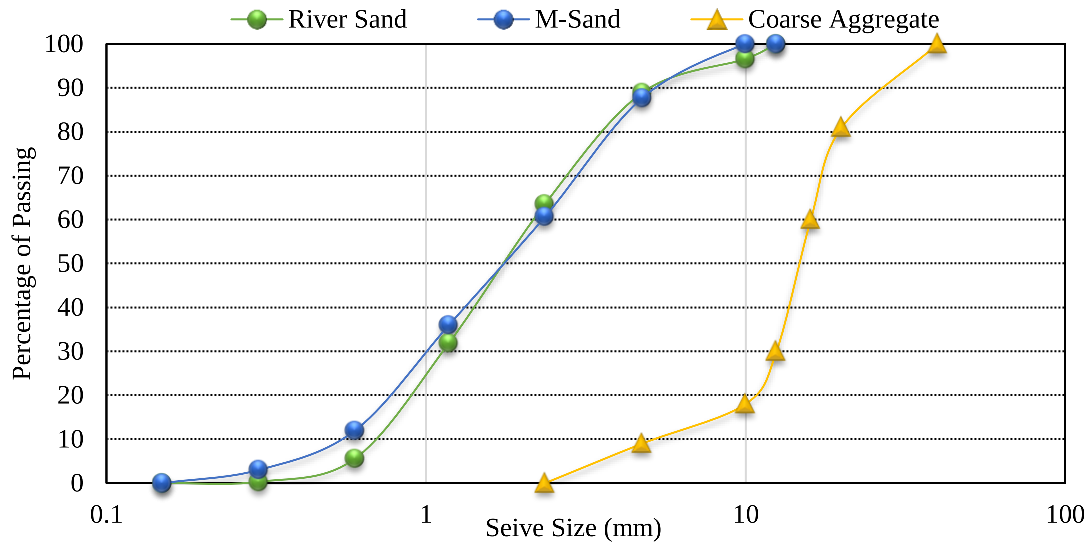

Fig. 1 Aggregate particle size distribution curves

2.3. Fibers

Two types of fibers were used, namely Polypropylene Fiber (PF) 0.5% and Steel Fibers (SF) 2% to enhance the mechanical properties. The micro monofilament polypropylene fiber (Figure 2a) is designed to meet ASTM C-1116 [18] standards and serves as a crack-control additive for cement-based materials. Steel fibers used in this study are hooked-end fibers, as shown in Figure 2b, and are characterized by their small size and specific shape, conforming to ASTM A820 M04 [19] standards. Both fibers were procured from a Dura flex steel fiber Kasturi metal composite limited. The properties of the fibers are detailed in Table 4, which is given by the supplier's technical datasheet. Steel and polypropylene fibers were selected for their complementary benefits: steel fibers enhance load-bearing capacity and crack control, while polypropylene fibers resist plastic shrinkage cracking and improve durability. Fiber lengths were based on literature [5]-[12] to optimize flexural strength, toughness, and workability in GPC.

Table 4. Properties of fibers

Description	Polypropylene Fiber	Steel Fiber
Aspect ratio	-	65
Specific gravity	0.91	-
Length	24/50	35
Diameter (micron)	28,40	0.55
Young's Modulus (MPa)	3500	-
Tensile strength (MPa)	346-560	1300

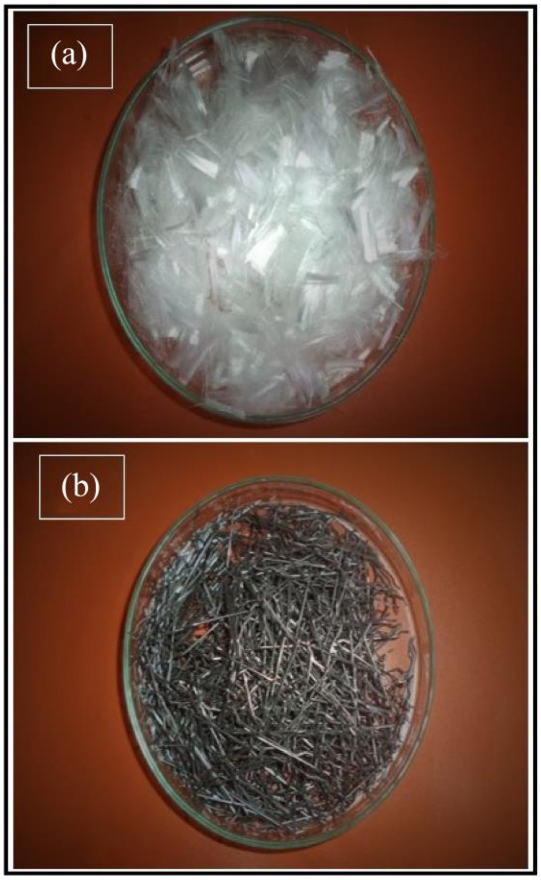

Fig. 2 Fibers (a) Polypropylene Fiber (b) Steel Fiber

2.4. Alkaline Activators

For the geopolymer concrete mixes, sodium hydroxide ($NaOH$) and sodium silicate (Na_2SiO_3) solutions were used as alkaline activators. $NaOH$ was used at an 8 M concentration, and the Na_2SiO_3 solution had a SiO_2/Na_2O ratio of 2.5. The properties of the activators are listed in Table 5, which is taken from the technical data sheet provided by the supplier [20, 21]. The NaOH solution was prepared by dissolving the solid NaOH pellets in water 24 hours before mixing, while the sodium silicate solution was used in its available commercial form.

Table 5. Properties of activators

Description	Sodium Hydroxide	Sodium Silicate
Chemical Formula	NaOH	Na_2SiO_3
Physical State	White, translucent pellets, flakes, or powder	Colourless to slightly coloured viscous liquid or solid (powder or beads)
Density (g/cm³)	Solid: 2.13 Liquid: 1.51	Solid: 1.4 - 1.6 Liquid: 1.37
Molecular Weight	40.00 g/mol	Approximately 122.06 g/mol
pH	Typically, around 14 (highly alkaline)	Typically, pH 11-12 (alkaline)

2.5. Mix Proportions and Casting

The concrete mixes were designed to achieve a target strength of M20 for conventional concrete, as per IS 10262:2019 [22]. For geopolymer concrete, the mix design was based on previous research and optimized for an 8 M molarity of NaOH. The proportions of materials for each mix, including binder content, aggregate ratio, fiber content, and activator ratios, were carefully adjusted to ensure consistency. The concrete was mixed in a pan mixer and poured into moulds for casting cubes (150x150x150mm), beams (500x100x100mm), and cylinders (300 mm height and 150mm dia) for testing. The mix proportions are listed in Table 6. The mix IDs are structured as A-B-C, where A represents the type of concrete (CC for Conventional Concrete and GPC for Geopolymer Concrete), B represents the type of fine aggregate used (R for River Sand and M for Manufactured Sand), and C represents the type of fiber added (PF for Polypropylene Fiber and SF for Steel Fiber).

For example, CC-M-SF refers to Conventional Concrete with Manufactured Sand and Steel Fiber, while GPC-R-PF refers to Geopolymer Concrete with River Sand and Polypropylene Fiber. This naming convention makes it easier to identify the composition of each mix.

Table 6. Mix proportion (kg/m^3)

Mix ID	Binder			Fine Aggregate		Coarse Aggregate	Water	Alkaline Activators (for GPC)		Fibers	
	Cement	Fly ash (70%)	GGBS (30%)	River sand	M-Sand			NaoH	Na2SiO3	PPF (0.5%)	SF (2%)
CC-R	330.00	-	-	767.10	-	1194.91	158.40	-	-	-	-
CC-M	330.00	-	-	-	767.10	1194.91	158.40	-	-	-	-
CC-R-PF	330.00	-	-	767.10	-	1194.91	158.40	-	-	1.65	-
CC-M-PF	330.00	-	-	-	767.10	1194.91	158.40	-	-	1.65	-
CC-R-SF	330.00	-	-	767.10	-	1194.91	158.40	-	-	-	6.60
CC-M-SF	330.00	-	-	-	767.10	1194.91	158.40	-	-	-	6.60
GPC-R	-	242.07	103.70	767.10	-	1194.91	32.44	15.26	119.27	-	-
GPC-M	-	242.07	103.70	-	767.10	1194.91	32.44	15.26	119.27	-	-
GPC-R-PF	-	242.07	103.70	767.10	-	1194.91	32.44	15.26	119.27	1.65	-
GPC-M-PF	-	242.07	103.70	-	767.10	1194.91	32.44	15.26	119.27	1.65	-
GPC-R-SF	-	242.07	103.70	767.10	-	1194.91	32.44	15.26	119.27	-	6.60
GPC-M-SF	-	242.07	103.70	-	767.10	1194.91	32.44	15.26	119.27	-	6.60

2.6. Curing and Testing

Conventional concrete specimens were cured in water for 28 days, following IS 516:1959 [23] guidelines. Geopolymer concrete specimens were cured at 60°C for 24 hours and left to air dry until testing. The mechanical properties, including compressive strength, modulus of rupture, and modulus of elasticity, were tested as per IS 516:1959 and IS 456:2000 [24]. Durability tests such as water absorption, sulphate resistance, and acid resistance were performed in accordance with ASTM C642 [25], ASTM C1012 [26] and ASTM C1896 [27].

3. Results and Discussion

3.1. Workability

The slump values for the various mix IDs reflect the influence of different parameters, such as the type of concrete, fine aggregate, and the inclusion of fibers. CC mixes generally show higher slump values compared to GPC mixes. This is consistent with the lower water content typically used in GPC mixes, contributing to reduced workability. Figure 3 illustrates the workability of the mixes.

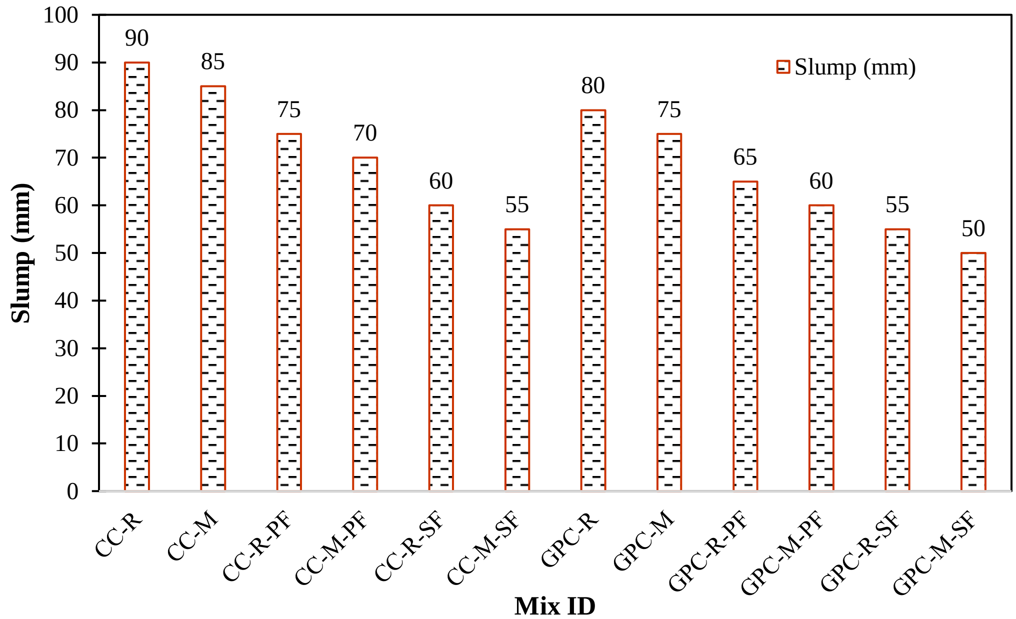

Fig. 3 Slump for the CC and GPC mixes

The slump values for conventional concrete mixes (CC-R and CC-M) are around 90 mm and 85 mm, respectively. This slightly higher slump in CC-R can be attributed to the smoother texture and rounder particles of river sand compared to the more angular and rougher texture of M-sand, which tends to absorb more water and reduces workability. When polypropylene fibers are incorporated into both CC and GPC mixes, the slump values reduce significantly due to the presence of the fibers, which increase the stiffness of the mix and reduce the free movement of particles. For instance, the slump value for CC-R-PF is 75 mm, while for CC-M-PF, it's slightly lower at 70 mm. A similar reduction pattern is observed in GPC-R-PF and GPC-M-PF, with 65 mm and 60 mm slump values, respectively. Steel fibers, being denser and stiffer than polypropylene Fibers, further reduce the slump values. This is observed in both CC and GPC mixes containing steel fibers, such as CC-R-SF and CC-M-SF, where slump values drop to 60 mm and 55 mm, respectively. In geopolymer concrete, GPC-R-SF shows a slump of 55 mm, and GPC-M-SF is expected to have the lowest slump of 50 mm. This can be attributed to the higher stiffness imparted by the steel fibers, which limits the concrete flow.

3.2. Mechanical Properties

3.2.1. Compressive Strength

The compressive strength of both CC and GPC was evaluated as per Indian Standard (IS 516:1959) at 7 and 28 days. The results are summarized in Table 7, and a bar chart is demonstrated in Figure 4.

Table 7. Mechanical properties

Mix ID	Compressive Strength (N/mm^2)		Modulus of Elasticity (N/mm^2)	Modulus of rupture (N/mm^2)
	7 days	28 days		
CC-R	20.08	30.97	31.38	4.17
CC-M	22.63	32.25	33.38	4.32
CC-R-PF	24.3	34.2	34.12	4.68
CC-M-PF	25.46	36.35	36.86	4.9
CC-R-SF	25.49	38.48	38.59	5.2
CC-M-SF	27.91	39.08	39.3	5.33
GPC-R	33.99	-	33.33	4.42
GPC-M	35.08	-	34.97	4.83
GPC-R-PF	35.57	-	35.71	4.91
GPC-M-PF	37.2	-	36.41	5.2
GPC-R-SF	46.69	-	38.8	5.82
GPC-M-SF	48.57	-	40.44	5.91

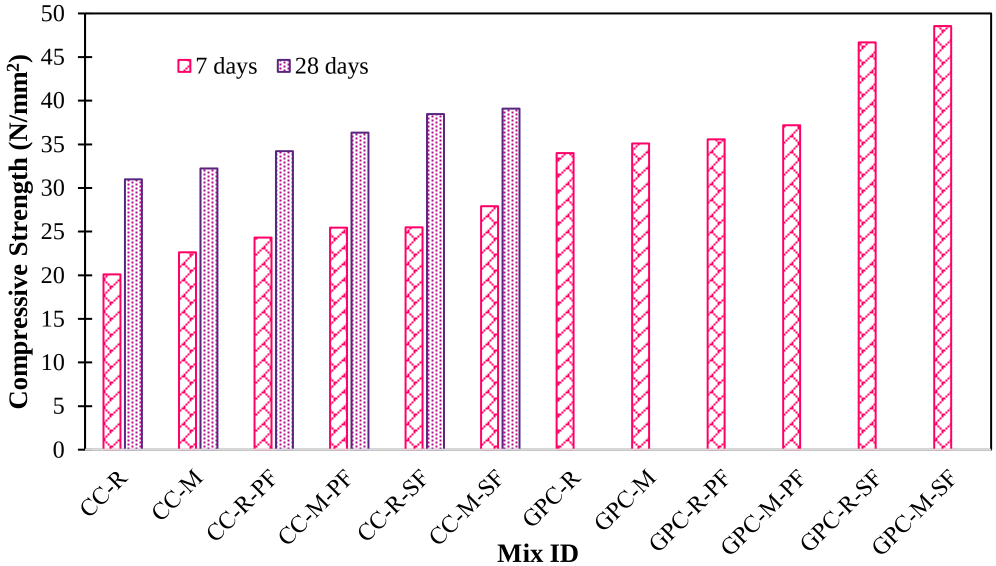

Fig. 4 Compressive Strength

In CC, the strength increased from 7 to 28 days due to the hydration of cement. For the control mix (CC-R), the 7-day strength was 20.08 N/mm², which increased to 30.97 N/mm² at 28 days, meeting the M20 grade requirements as per IS 456:2000. Similar trends were observed for other CC mixes, with CC-M reaching 32.25 N/mm² at 28 days. The inclusion of polypropylene fibers in CC-R-PF and CC-M-PF enhanced the strength slightly, while steel fiber-reinforced mixes (CC-R-SF and CC-M-SF) achieved the highest compressive strengths at 28 days, 38.48 N/mm² and 39.08 N/mm², respectively. Steel fibers contributed significantly by enhancing crack resistance and load-bearing capacity. The GPC mixes showed notably higher early strength compared to conventional concrete. GPC-R and GPC-M exhibited 7-day strengths of 33.99 N/mm² and 35.08 N/mm², respectively, far exceeding the typical 28-day strengths of M20 concrete. Fiber-reinforced GPC mixes, especially those with steel fibers (GPC-R-SF and GPC-M-SF), demonstrated exceptional performance, achieving 46.69 N/mm² and 48.57 N/mm² at 7 days. This rapid strength development results from the geopolymerization process, which does not rely on cement hydration.

Alkaline activators like sodium hydroxide and sodium silicate react with the aluminosilicate materials in fly ash and GGBS to form a dense, three-dimensional geopolymer matrix. This matrix is more compact and less porous than the hydration products in conventional concrete, leading to higher early-age and long-term compressive strengths. The use of M-sand, with its angular particles and superior gradation, enhances the packing density of the concrete matrix, reducing voids and increasing strength. This is particularly evident in the GPC mixes, where the combination of M-sand and the geopolymer binder results in a denser and stronger matrix. Further, the inclusion of polypropylene fibers and steel fibers in the concrete mix improves the mechanical interlocking within the matrix. Steel fibers, in particular, bridge micro-cracks and prevent their propagation, resulting in a significant increase in compressive strength observed in the steel fiber-reinforced mixes.

3.2.2. Modulus of Rupture

The modulus of rupture (flexural strength) tests were conducted based on the Indian Standard IS 516:1959 to evaluate the tensile performance of the concrete mixes. The results are shown in Table 7, illustrated as a line graph in Figure 5. The control mix of conventional concrete (CC-R) exhibited a modulus of rupture of 4.17 N/mm², while the mix using manufactured sand (CC-M) showed a slight improvement to 4.32 N/mm². With the addition of fibers, the flexural strength further improved. The polypropylene fiber-reinforced concrete (CC-R-PF and CC-M-PF) recorded values of 4.68 N/mm² and 4.9 N/mm², respectively. The steel fiber-reinforced mixes (CC-R-SF and CC-M-SF) showed significantly higher values, with CC-R-SF at 5.2 N/mm² and CC-M-SF at 5.33 N/mm², highlighting the superior performance of steel fibers in improving the flexural strength of conventional concrete.

In comparison, geopolymer concrete (GPC) performed better overall. The geopolymer control mix (GPC-R) demonstrated a modulus of rupture of 4.42 N/mm², which was already higher than the conventional concrete control mix. Including M-sand (GPC-M) further improved the modulus of rupture to 4.83 N/mm². The introduction of polypropylene fibers resulted in a notable increase in flexural strength, with values of 4.91 N/mm² for GPC-R-PF and 5.2 N/mm² for GPC-M-PF. The highest values were recorded for steel fiber-reinforced geopolymer concrete (GPC-R-SF and GPC-M-SF), with flexural strengths of 5.82 N/mm² and 5.91 N/mm², respectively.

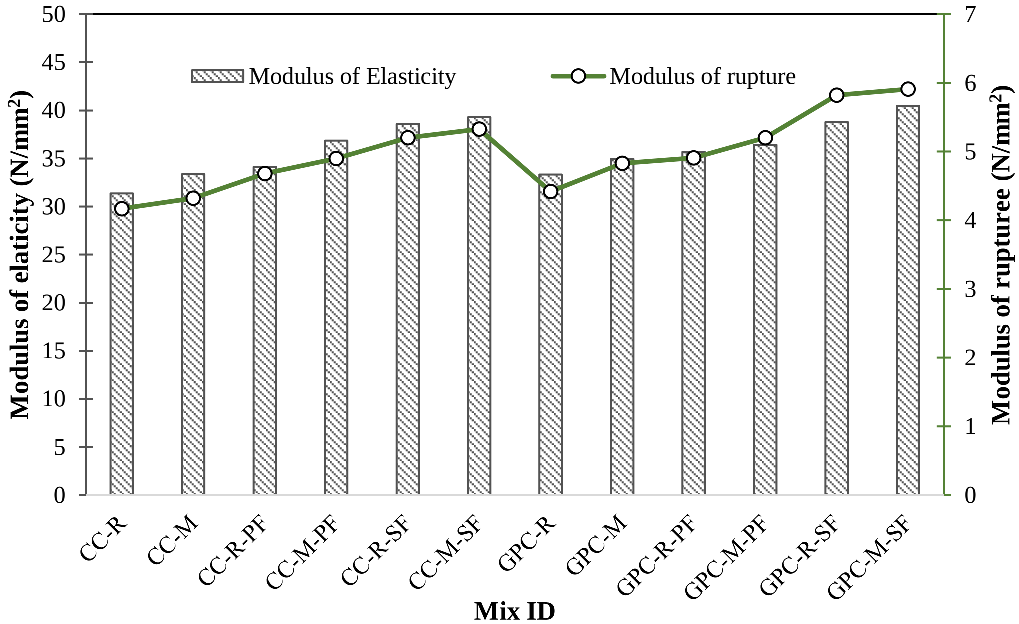

Fig. 5 Modulus of rupture and modulus of elasticity

According to IS 456:2000, the typical range for the modulus of rupture for normal concrete is around 3–5 N/mm², depending on the grade of concrete. The values achieved in this study for both conventional and geopolymer concretes, particularly those incorporating steel fibers, exceed the typical ranges, indicating enhanced flexural performance, which is critical for structural applications where resistance to bending is essential. The reasons for this variation include stronger bonding in GPC, improved performance with M-Sand and the impact of fiber reinforcement. The geopolymer matrix provides superior bonding compared to the C-S-H gel in conventional concrete, leading to enhanced tensile strength. The polymerization process in GPC creates a continuous network of aluminosilicate bonds, contributing to its higher flexural strength. The angular and rough texture of M-sand improves the interlocking of particles, leading to better stress distribution and higher flexural strength. This is particularly beneficial in GPC, where the matrix is already denser and stronger. Fibers, especially steel fibers, are crucial in enhancing flexural strength by bridging cracks and preventing their propagation. The presence of steel fibers in the GPC-M-SF mix contributed to its superior flexural strength by increasing the load-carrying capacity and energy absorption before failure. The GPC-M-SF mix outperformed all other mixes, demonstrating that the combination of M-sand and steel fibers in GPC significantly enhances its tensile performance.

3.2.3. Modulus of Elasticity

Concrete's modulus of elasticity (E) is a crucial parameter reflecting the material’s stiffness and ability to deform under load. The results are presented in Table 7 and represented as a bar chart in Figure 5.

In CC, the modulus of elasticity ranges from 31.38 N/mm² for the CC-R mix (river sand with no fibers) to 39.30 N/mm² for the CC-M-SF mix (M-sand with steel fibers). As per the Indian Standard IS 456:2000, the modulus of elasticity generally correlates with the compressive strength of the concrete, which explains the observed trend. The CC-R mix shows the lowest modulus due to its lower compressive strength and the absence of fibers. The introduction of steel fiber significantly improves stiffness due to its reinforcement effect, which enhances load distribution and reduces deformation under stress. GPC shows a similar trend, with the modulus of elasticity increasing from 33.33 N/mm² for GPC-R to 40.44 N/mm² for GPC-M-SF. The higher values for GPC mixes are attributed to the denser microstructure of geopolymer concrete, which provides enhanced stiffness compared to conventional concrete. Additionally, the inclusion of fibers in GPC further increases the modulus due to the fiber-matrix interaction, particularly with steel fibers, which significantly enhance the stiffness of the matrix.

The stress-strain curve (Figure 6) plotted for these mixes further corroborates the trends in modulus of elasticity. For both CC and GPC, the mixes with steel fibers show a steeper slope in the stress-strain curve, indicating a higher modulus and stiffness. Polypropylene fibers, while improving the modulus slightly compared to plain concrete, exhibit a more gradual slope than steel fiber-reinforced mixes, reflecting their relatively lower contribution to stiffness. This behaviour is consistent with the expected mechanical properties of fibers and the influence of geopolymer binders in GPC mixes.

The observed variations in the modulus of elasticity align with the IS 456:2000 standard, which suggests a proportional relationship between the modulus of elasticity and the compressive strength of concrete. Including fibers, particularly steel fibers, improves the load-bearing capacity and reduces strain under applied stress, leading to higher modulus values. The denser matrix of GPC also contributes to higher stiffness, making it a more robust material than conventional concrete, especially under static loading conditions. The stress-strain graphs further emphasize these differences, with fiber-reinforced and geopolymer mixes showing enhanced performance.

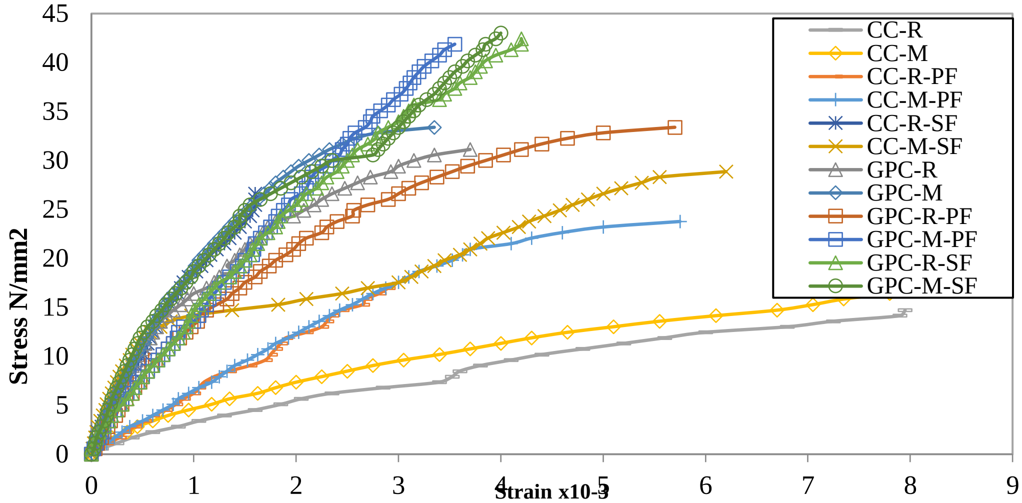

Fig. 6 Stress-strain curves

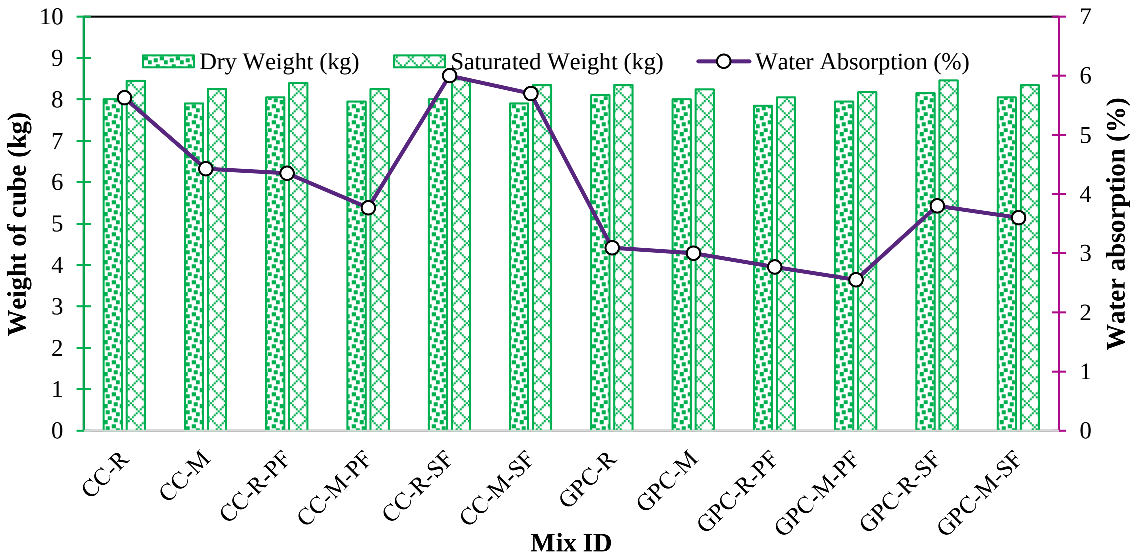

Fig. 7 Weight of cubes and water absorption

3.3. Durability Properties

3.3.1. Water Absorption

The water absorption test results for various concrete mixes, including both CC and GPC, were analysed and compared to the standard range provided by ASTM C642. According to ASTM C642, conventional concrete's typical range of water absorption is 3% to 7%, depending on its porosity and mix design. The test results are listed in Table 8 and represented as a bar chart in Figure 7. Water absorption values for the tested conventional concrete mixes ranged from 3.77% to 6.00%, aligning with the ASTM standards. The mixes containing steel fibers (CC-R-SF and CC-M-SF) exhibited higher absorption rates within this range, likely due to increased porosity caused by micro-cracks around the steel fibers, despite their positive impact on mechanical strength.

Meanwhile, polypropylene fiber mixes (CC-R-PF and CC-M-PF) showed lower absorption values due to the hydrophobic properties of the fibers, which helped mitigate water ingress. For GPC mixes, the water absorption ranged between 2.55% and 3.80%. These values are significantly lower than the absorption values for conventional concrete, showcasing the superior performance of GPC regarding water impermeability. The lower absorption in GPC can be attributed to the dense matrix formed by the alkali-activated fly ash (70%) and GGBS (30%) binders, reducing capillary pores and limiting water absorption. According to ASTM C642, well-cured and dense concretes often show water absorption values of around 2% to 3%, and the GPC results, particularly for mixes with polypropylene fibers (GPC-M-PF at 2.55%), fall within this high-performance range. Steel fiber-reinforced GPC mixes (GPC-R-SF and GPC-M-SF) showed slightly higher absorption, similar to the trend in conventional concrete, but remained within acceptable limits.

Table 8. Water absorption test results

Mix ID	Dry Weight (kg)	Saturated Weight (kg)	Water Absorption (%)
CC-R	8.00	8.45	5.63
CC-M	7.90	8.25	4.43
CC-R-PF	8.05	8.40	4.35
CC-M-PF	7.95	8.25	3.77
CC-R-SF	8.00	8.48	6.00
CC-M-SF	7.90	8.35	5.70
GPC-R	8.10	8.35	3.09
GPC-M	8.00	8.24	3.00
GPC-R-PF	7.85	8.05	2.77
GPC-M-PF	7.95	8.17	2.55
GPC-R-SF	8.15	8.46	3.80
GPC-M-SF	8.05	8.34	3.60

Table 9. Sulphate resistance test results

Mix ID	Compressive strength (N/mm^2)		Reduction in strength (%)
	Water curing (CC) and ambient curing (GPC)	After Sulphate curing	
CC-R	30.97	27.16	12.30
CC-M	32.25	28.66	11.14
CC-R-PF	34.20	30.57	10.62
CC-M-PF	36.35	32.64	10.21
CC-R-SF	38.48	35.12	8.73
CC-M-SF	39.08	35.91	8.12
GPC-R	33.99	31.06	8.61
GPC-M	35.08	32.19	8.23
GPC-R-PF	35.57	32.77	7.86
GPC-M-PF	37.20	34.32	7.74
GPC-R-SF	46.69	43.41	7.03
GPC-M-SF	48.57	45.21	6.91

3.3.2. Sulphate Resistance

Following the guidelines in ASTM C1012, the sulphate resistance test was conducted to evaluate their durability in sulphate-rich environments on both CC and GPC mixes after 28 days of water curing for CC and ambient for GPC. The specimens were exposed to a 5% sodium sulphate (Na2SO4) solution for 28 days. The test results (Table 9) indicated a reduction in compressive strength for all mixes, though the extent of reduction was considerably lower compared to the acid resistance test. Based on the test results, Figure 8 illustrates the sulphate resistance.

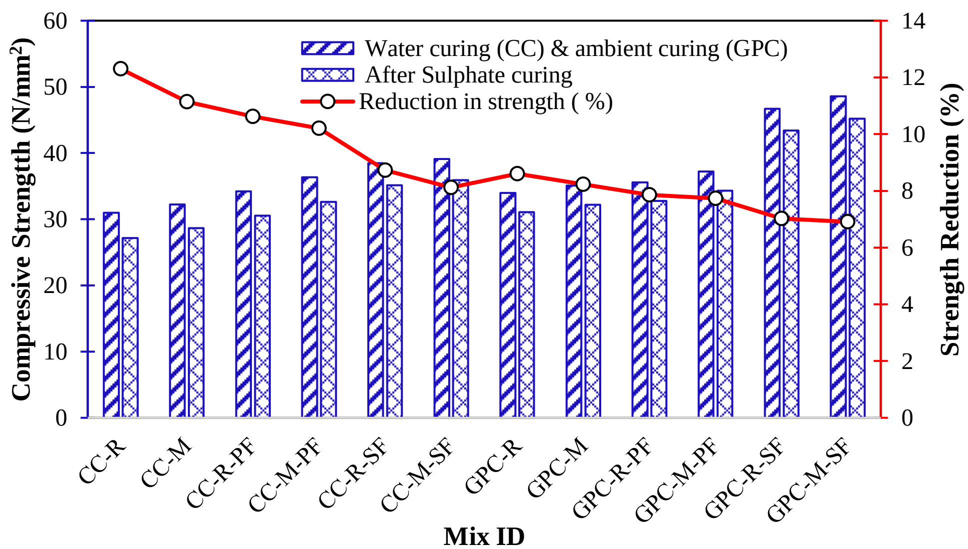

Fig. 8 Sulphate resistance

The reduction in strength for CC mixes ranged from 8.12% to 12.30%, with CC-R showing the highest reduction (12.30%). The addition of fibers, both polypropylene and steel fibers, enhanced the sulphate resistance of CC, as seen in the reduced strength loss for CC-M-PF (10.21%) and CC-M-SF (8.12%). The performance of CC-M-SF was the most notable among the conventional concrete mixes, exhibiting a reduction of only 8.12%. Incorporating fibers helps mitigate sulphate-induced deterioration by reducing crack propagation and improving the structural integrity of the concrete. The GPC mixes exhibited superior sulphate resistance, with strength reductions between 6.91% and 8.61%. GPC-M-SF performed the best, with only a 6.91% reduction in strength, further confirming that steel fibers significantly enhance the sulphate resistance of GPC. The enhanced performance of GPC compared to CC can be attributed to the lower calcium content in GPC, which limits the formation of expansive products such as gypsum and ettringite that typically cause sulphate attacks in conventional Portland cement concrete.

3.3.3. Acid Resistance

The acid resistance test was performed for the mixes as per ASTM C1896 after 28 days of water curing for CC and ambient curing for GPC. The specimens were then subjected to 5% sulphuric acid (H2SO4) solution for 28 days to assess their durability under acidic conditions. The results showed that the compressive strength of all mixes reduced significantly after acid curing, with reductions ranging from 25.31% to 34.08%. The results of the acid resistance test are displayed in Table 10 and are represented as a bar chart in Figure 9.

Conventional concrete exhibited higher strength reductions compared to GPC. The CC mixes had reductions between 28.14% and 34.08%, with the CC-R mix showing the highest reduction in strength (34.08%). The introduction of PF and SF fibres improved acid resistance in CC, as evidenced by the lower reduction percentages for CC-M-PF (30.11%) and CC-M-SF (28.14%).

Table 10. Acid resistance test results

Mix ID	Compressive strength (N/mm^2)		Reduction in strength (%)
	Water curing (CC) and ambient curing (GPC)	After Acid curing	
CC-R	30.97	20.42	34.08
CC-M	32.25	21.31	33.92
CC-R-PF	34.20	23.88	30.18
CC-M-PF	36.35	25.41	30.11
CC-R-SF	38.48	27.42	28.73
CC-M-SF	39.08	28.08	28.14
GPC-R	33.99	24.35	28.36
GPC-M	35.08	25.20	28.15
GPC-R-PF	35.57	25.81	27.45
GPC-M-PF	37.20	27.22	26.83
GPC-R-SF	46.69	34.73	25.62
GPC-M-SF	48.57	36.28	25.31

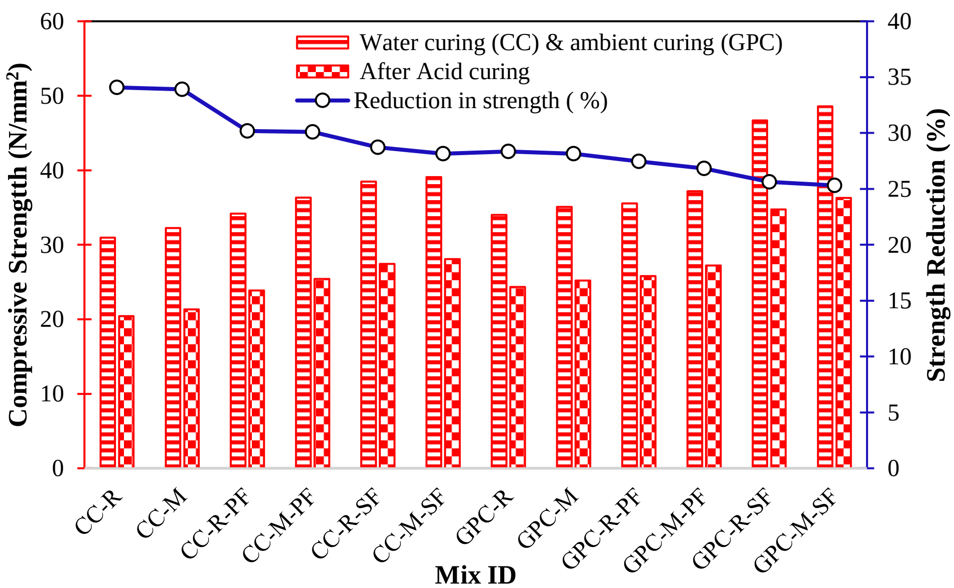

Fig. 9 Acid resistance

This improvement is due to the fibers ability to bridge cracks and reduce micro-crack propagation, which mitigates the effects of acid ingress. In contrast, GPC mixes demonstrated better acid resistance, with strength reductions ranging between 25.31% and 28.36%. GPC-M-SF showed the lowest strength reduction (25.31%), indicating the superior performance of geopolymer concrete reinforced with steel fibers in resisting acid attack. The lower reduction in strength for GPC can be attributed to its denser microstructure formed by the geopolymerization process, which reduces the porosity and limits the penetration of aggressive chemicals. Additionally, using fly ash and GGBS as binders in GPC contributes to its enhanced chemical resistance due to the lower calcium content compared to conventional concrete, making GPC less prone to degradation in acidic environments.

3.4. Environmental and Economic Benefits of Fiber-Reinforced GPC

Fiber-reinforced geopolymer concrete offers substantial environmental and economic advantages over conventional concrete, especially in contexts like Tamil Nadu, India. A key environmental benefit lies in GPC's reliance on industrial by-products, such as fly ash and GGBS, which replace traditional Portland cement. This substitution significantly lowers greenhouse gas emissions associated with cement production, reducing the overall carbon footprint of construction.

The economic analysis (Table 11) highlights the comparative material costs of GPC and CC mixes based on local market prices. For instance, the cost of sodium silicate and sodium hydroxide, crucial activators in GPC, contribute to higher initial material expenses compared to CC. For example, GPC-M is approximately 6.5 times higher than CC-M. This initial increase is offset by the long-term durability, reduced maintenance, and extended lifespan of GPC, which reduce lifecycle costs. Incorporating fibers, specifically steel (SF) and polypropylene fibers (PPF), further enhances GPC's mechanical properties, improving crack resistance and durability. This makes GPC especially suitable for infrastructure requiring resilience against environmental degradation, such as marine structures, bridges, and sustainable buildings. The enhanced durability translates to lower maintenance and replacement costs over time, providing economic value despite the higher initial investment. Another consideration is the scalability of GPC production. Currently, the limited adoption of GPC in construction contributes to higher material costs. However, if GPC usage expands, economies of scale will likely drive down the costs of activators and other components, making it more competitive with conventional concrete on a per-kilogram basis.

This potential for cost reduction further strengthens GPC's viability as a sustainable construction material. A life cycle assessment (LCA) of GPC demonstrates reduced environmental impact compared to CC, with a lower carbon footprint and fewer end-of-life disposal concerns. The extended lifespan and minimized environmental degradation make fiber-reinforced GPC an attractive choice for eco-conscious projects aiming to meet sustainability targets without compromising on structural performance.

Table 11. Cost comparison as per mix proportions (rupees)

Mix ID	Binder			Fine Aggregate		Coarse Aggregate	Water	Alkaline Activators		Fibres		Total Cost per m^3
	Cement	Fly ash	GGBS	River sand	M-Sand			NaoH	Na_2SiO_3	PF	SF	
CC-R	2970	-	-	1150	-	1195	-	-	-	-	-	5314
CC-M	2970	-	-	-	767	1195	-	-	-	-	-	4931
CC-R-PF	2970	-	-	1150	-	1195	-	-	-	198	-	5512
CC-M-PF	2970	-	-	-	767	1195	-	-	-	198	-	5129
CC-R-SF	2970	-	-	1150	-	1195	-	-	-	-	858	6172
CC-M-SF	2970	-	-	-	767	1195	-	-	-	-	858	5789
GPC-R	-	2420	1244	1150	-	1195	-	1678	25643	-	-	33329
GPC-M	-	2420	1244	-	767	1195	-	1678	25643	-	-	32946
GPC-R-PF	-	2420	1244	1150	-	1195	-	1678	25643	198	-	33527
GPC-M-PF	-	2420	1244	-	767	1195	-	1678	25643	198	-	33144
GPC-R-SF	-	2420	1244	1150	-	1195	-	1678	25643	-	858	34187
GPC-M-SF	-	2420	1244	-	767	1195	-	1678	25643	-	858	33804

4. Conclusion

This study evaluated the workability, mechanical properties, and durability of fiber-reinforced geopolymer concrete and conventional concrete mixes incorporating polypropylene and steel fibers. The following conclusions can be drawn from the experimental investigation and broader implications for practical applications:

The workability of both conventional and geopolymer concrete decreased with fiber addition, particularly steel fibers. Geopolymer concrete showed lower slump values than conventional concrete. However, it remained within acceptable limits, supporting their use in applications requiring moderate workabilities, such as precast elements and non-pumped concrete structures.

The compressive strength is enhanced with fiber reinforcement of both concrete types, with GPC-M-SF showing the best performance due to geopolymerization and fiber synergy. Geopolymer concrete excelled, especially at its early stages, and it has potential for high-strength applications, including structural beams and columns in aggressive environments where durability is critical.

Fibre-reinforced geopolymer mixes' flexural strength (modulus of rupture) showed notable improvement compared to conventional mixes. Steel fibers provided better crack resistance and improved load distribution, resulting in the highest flexural strength among all tested mixes. This characteristic suits applications requiring enhanced bending performance, such as bridge decks, pavements, and marine structures.

The modulus of elasticity increased by including fibers in both concrete types. Steel fiber-reinforced geopolymer mixes exhibited the highest modulus of elasticity, enhancing the material's resistance to deformation under load. This feature is beneficial in applications where stiffness and load-bearing capacity are essential, including slabs and heavy-duty flooring.

Fiber-reinforced geopolymer mixes demonstrated superior durability when subjected to water absorption, sulphate resistance, and acid resistance tests. The reduced porosity and improved microstructure due to geopolymerization, along with fiber reinforcement, significantly enhanced the sulphate and acid resistance of the GPC mixes. The steel fiber-reinforced geopolymer mix (GPC-M-SF) exhibited the least strength reduction in aggressive environments. This makes GPC a promising alternative for infrastructure exposed to aggressive environments, such as wastewater treatment plants, coastal installations, and chemical storage facilities.

In summary, this study demonstrates that fiber-reinforced GPC, particularly with steel fibers, offers a high-performance, durable, and sustainable alternative to conventional concrete. However, GPC currently incurs a higher upfront cost, and its long-term environmental and economic benefits make it a viable alternative to CC, particularly as adoption grows and production costs decrease.

4.1. Limitations and Future Recommendations

This study focused on the initial mechanical and durability properties of fiber-reinforced GPC but did not assess long-term durability in real-life conditions. Future research should evaluate GPC's resilience to prolonged chemical exposure, temperature fluctuations, and freeze-thaw cycles. Potential applications include structural elements such as bridge decks, marine structures, and precast panels, where enhanced tensile strength and crack resistance are vital. Further studies could investigate optimal fiber content, alternative eco-friendly binders, and recycled aggregates to improve GPC's sustainability and cost-effectiveness for broader infrastructure projects.

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